USACERL Technical Report M-91/09
November 1990
Electromagnetic Properties of High Tc Superconducting Materials

US Army Corps of Engineers
Construction Engineering Research Laboratory

Selective Screening of High Temperature Superconductors by Resonant Eddy Current Analysis

by
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Electromagnetic shielding is often required in the design and construction of Army facilities and equipment to protect electrical systems or electronic components from the effects of unwanted electromagnetic energy. With the discovery of High Transition Critical Temperature Superconducting (HiTcS) compounds in 1987, researchers immediately sought electromagnetic applications for these novel materials. Before use, these compounds must be tested. The purpose of this study was to develop an alternate screening analysis to supplement the traditional resistive methods of assessing HiTcS compounds' practicality for electromagnetic applications.

This report sets forth both the principle and practice of Resonant Eddy Current Analysis (RECA) and its applicability as a screening agent for prospective High Temperature Superconductors. The RECA methodology is a contactless, timely, and efficient alternative to traditional resistive methods for ascertaining existence of superconductivity. It can provide an accurate measure of a sample's bulk critical current density. It is inexpensive, requiring only an inductor, several capacitors, and an impedance meter. Its high intrinsic sensitivity can be maximized. The method provides a definitive signature unique to superconductors undergoing a magnetic phase transition. It does not require the conducting regions of a given sample to be contiguous and can provide valuable sample quality information for properly thermostated samples.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE
November 1990

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Selective Screening of High Temperature Superconductors by Resonant Eddy Current Analysis

5. FUNDING NUMBERS
PR AT23
WU MA-E99

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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PO Box 4005
Champaign, IL 61824-4005

8. PERFORMING ORGANIZATION REPORT NUMBER
TR M-91/09

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Army Corps of Engineers
20 Massachusetts Avenue NW
Washington D.C. 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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This report sets forth both the principle and practice of Resonant Eddy Current Analysis (RECA) and its applicability as a screening agent for prospective High Temperature Superconductors. The RECA methodology is a contactless, timely, and efficient alternative to traditional resistive methods for ascertaining existence of superconductivity. It can provide an accurate measure of a sample's bulk critical current density. It is inexpensive, requiring only an inductor, several capacitors, and an impedance meter. Its high intrinsic sensitivity can be maximized. The method provides a definitive signature unique to superconductors undergoing a magnetic phase transition. It does not require the conducting regions of a given sample to be contiguous and can provide valuable sample quality information for properly thermostated samples.

14. SUBJECT TERMS
quality assurance
superconductivity
noninvasive measurements
resonant circuits
resistive measurements

15. NUMBER OF PAGES
14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

FOREWORD

This study was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A161102AT23, "Basic Research in Military Construction," Work Unit MA-E99 "Electromagnetic Properties of High Tc Superconducting Materials."

This research was performed by the Engineering and Materials Division (EM) of the U.S. Army Construction Engineering Research Laboratory (USACERL). Dr. Paul A. Howdyshell is Acting Chief of USACERL-EM. The technical editor was Gloria J. Wienke, USACERL Information Management Office.

COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L. R. Shaffer is Technical Director.

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SELECTIVE SCREENING OF HIGH TEMPERATURE SUPERCONDUCTORS BY RESONANT EDDY CURRENT ANALYSIS

1 INTRODUCTION

Background

Electromagnetic shielding is often required in the design and construction of Army facilities and equipment to protect electrical systems or electronic components from the effects of unwanted electromagnetic energy. This energy may cause the equipment to malfunction or may damage or destroy it. Although many sources of electromagnetic interference (EMI)* generate sufficient energy in stray or unwanted electromagnetic fields to cause electronic equipment to malfunction, damage from these sources is unlikely. The possibility of damage is greatest from the high energy contained in an electromagnetic pulse (EMP) resulting from a nuclear detonation or from the high currents associated with a lightning stroke.

The most common method of providing protection against EMP is to place the equipment in electromagnetically shielded zones within a hardened facility. Such shielded zones are typically constructed of materials that have high conductivities and magnetic permeabilities, both of which can substantially increase the cost and weight of the resulting structure.

With the discovery of High Transition Critical Temperature Superconducting (HiTcS) compounds in 1987, researchers immediately sought electromagnetic applications for these novel materials. Superconductors have a number of properties that distinguish them from otherwise normal materials. When a superconductor is cooled below a certain temperature (referred to as the critical temperature, T_c) the material quickly loses all resistance to the passage of direct electrical currents and is said to have become superconducting. This transition is simultaneously accompanied by the expulsion of magnetic flux from the sample's interior (the Meissner effect). Under these conditions, the electrical conductivity becomes so high it is unmeasurable; the material may be thought of as a perfect conductor. At the same time, the magnetic permeability becomes vanishingly low; the material is said to be a perfect diamagnet. Collectively, these two parameters define the steady-state dc field properties of a superconductor. However, if the imposed electromagnetic fields vary over time, these electrical parameters assume finite values somewhere between their normal values and the dc superconducting limit. Because both electrical and magnetic components are natural constituents of an electromagnetic pulse, the unique combination of magnetic flux expulsion and concurrent high electrical conductivity of superconductors make them prime candidates for EMP shields.

During the years since the discovery of HiTcS compounds, an enormous effort has been put forth by the world's scientific community to characterize the essential physics of these materials. A principal impediment to the preparation of quality HiTcS compounds is the fact they are classified as ceramics at

* "Electromagnetic interference" is a general term commonly used to describe any type of radiated electromagnetic energy that may interfere with operation of electrical equipment or instrumentation. Nuclear electromagnetic pulse is a specific type of EMI having the form of a single pulse of electromagnetic energy. The shape and magnitude of the pulse (which determines its spectral energy density content) is predictable for various threats. Radio frequency interference is another specific kind of EMI within radio frequency spectrum.

room temperature and have all the attendant materials problems that the more traditional "low temperature superconductors" do not have (being metallic conductors at room temperature).

The primary feature distinguishing HiTcS from low temperature superconductors is that their transition temperatures are near -180 °C or higher. This makes it possible to cool them below their transition temperatures by using liquid nitrogen, an inexpensive and readily available cryogen. This fact alone permits applications not associated with shielding, such as High-Q microwave cavities, to be constructed in noncryogenic laboratories, and makes them reasonably accessible for field use. Further, there are natural environments, such as earth orbits, where surfaces shielded from direct solar glare can achieve ambient temperatures below the transition temperature of these new HiTcS compounds.

In July 1985, the Secretary of the Army established the U.S. Army Construction Engineering Research Laboratory (USACERL) as the Army's lead agency for large space structures technology in support of the U.S. Army Mission in Space. The space environment presents competing and often contradictive requirements for shielding materials in general. The need for innovative thinking on these matters led to considering these newly discovered HiTcS compounds as natural EMP shields and is, in part, the motivation of this study.

Ongoing research with these HiTcS compounds has underscored the fact that it is the quality of their crystal structure that defines their electromagnetic applicability. The crystal structure quality determines the surface impedance of the material (important at microwave frequencies) and the critical current density, which is crucial in magnetics.[1] To date, some of the best and most reproducible crystal preparations occur through thin film deposition techniques, which inherently can maximize the essential two-dimensional character of HiTcS compounds. A sample's quality may then be checked by a combination of analytic methods such as x-ray diffraction, magnetic susceptibility, and resistance vs temperature curves. This last method provides a traditional measure of sample quality and enables a measurement of the critical current density. However, an artifact of the measurement (resistive heating in the electrical contacts) can cause samples to fail the critical current measurement prematurely. This sensitivity to the critical current density, J_c, of a transported current (or equivalently the resulting magnetic field) is a general property of all superconductors and reflects the fact that J_c tends to zero as any local portion of a superconductor's temperature approaches Tc.[2] Further, in any development program, a large number of samples must be tested as a function of various processing parameters. Resistive measurements can be both labor intensive and time consuming, and evoke the need for a quick and efficient screening method for potential samples.

For several years, USACERL has maintained an abiding interest in HiTcS compounds for the purpose of EMP shielding. A particular interest has existed in evaluating these compounds from a large number of sources in order to define optimal crystal structures/process parameters. Appropriate samples would be candidates for the MIL-STD-285[3] shielding test at frequencies ranging from 0.1 to 10.0 MHz (magnetic). The inductive nature of this test suggested Resonant Eddy Current Analysis (RECA) as a

[1] "Interview with Venky Venkatesan", *Supercurrents*, Vol 9 (July 1989), pp 49-58.

[2] T.G. Berlincourt and R.R. Hake, "Superconductivity at High Magnetic Fields," *Physical Review*, Vol 131 (1963), p 140; Y. Shapira and L.J. Neuringer, "Upper Critical Fields of Nb-Ti Alloys: Evidence for the Influence of Pauli Paramagnetism," *Physical Review* Vol 140 (29 November 1965), p A1638; S. Foner, et al., "Upper Critical Fields of High-Temperature Superconducting $Nb_{1-y}(Al_{1-x}Ge_x)$ and Nb_3Al: Measurements of $H_{c2} > 400$ kG at 4.2°K," *Physics Letters*, Vol 31A, #7 (6 April 1970), p 349.

[3] Military Standard (MIL-STD) 285, Attenuation Measurements for Enclosures, Electromagnetic Shielding for Electronic Test Purposes, Method of (25 June 1956).

practical screening agent for potential HiTcS samples because it does not have the aforementioned drawbacks of purely resistive ("4-probe") methods. The RECA system is the subject of this technical report and although the fundamental methodology is not new[4], its use as a screening agent represents a sensitive, inexpensive, umely, and efficient alternative to traditional resistive methods.

Objective

The purpose of this study is to develop an alternate screening analysis to supplement the more traditional resistive methods of assessing the appropriateness of HiTcS compounds as candidates for EMP shielding and other electromagnetic applications.

Approach

The development of a RECA method for testing superconductors involved two major efforts: (1) a literature search, and (2) rendering the results of the search into a workable system through empirical studies.

A literature search was performed to keep abreast of the rapid progress made in the general field of superconductivity, and to provide a summary of previous efforts involving inductive analysis of materials.[5] Such a search necessarily included archival literature in electromagnetics which was used to provide a mathematical formulation for the empirical studies. Such studies heavily rely on classical electromagnetic theory to render the changes of a superconductors' physical parameters into the canonical variables associated with traditional circuit theory. The choice of which particular variable would be optimally sensitive to a given physical parameter is not *a priori*, and was in part responsible for guiding these initial empirical studies.

Mode of Technology Transfer

The results of this investigation will be incorporated into ongoing 6.1 and 6.2 Research, Development, Test, and Evaluation (RDTE) programs. It is recommended that a summary of information gained from this study be incorporated in Technical Manual (TM) 5-855-5, *Nuclear Electromagnetic Pulse (NEMP) Protection* (Department of the Army, February 1974).

[4] A.L. Schawlow and G.E. Devlin, "Effect of Energy Gap on the Penetration Depth of Superconductors," *Physical Review*, Vol 113 (#1) (January 1, 1959) pp 120-126.

[5] C.V. Dodd; et al, *Some Eddy-Current Problems and Their Integral Solutions*, ORNL-4384 (April 1969); C.V. Dodd and W.E. Deeds, "Absolute Eddy-Current Measurement of Electrical Conductivity," in *Review of Progress in Quantitative Nondestructive Evaluation*, Vol 1 (1982); C.V. Dodd and W.E. Deeds "Analytical Solutions to Eddy-Current Probe-Coil Problems," *Journal of Applied Physics*, Vol 39, No. 6 (May 1968).

2 PROCEDURE

The essence of the RECA methodology is to use an alternating current electrical circuit in a configuration in which the observable electronic parameters are both stable and well defined. Further, if the circuit possesses a resonance, then it has well characterized parameters and a large signal to noise ratio. This situation allows for great sensitivity and selectivity, which makes it ideal for use as a screening agent sensitive to small changes in a sample's properties. For a superconductor, the electrical parameters of interest are the electrical conductivity, σ, and the magnetic permeability μ; both are relevant for EMP shielding. These two parameters undergo large changes in their electrical values when the superconducting material is either warmed or cooled through the superconducting transition temperature. The large changes in these material properties coupled with RECA sensitivity creates an ideal screening signature capable of detecting even very small amounts of a superconductor (which need not necessarily be contiguous).

Description

The rendering of a changing material property into an electrical signal appropriate as a screening signature can be accomplished by designing a "lumped circuit" parameter sensitive to the particular material property. Since superconductors undergo intrinsic magnetic phase transitions when cooled (or warmed) through the transition temperature, a simple inductor is the component of choice. An inductor may be considered (in some approximation) to have a particular value of inductance depending on the density of flux lines linking the constituate coils. When a superconducting or normal material is inserted within the volume of the inductor, the density of the flux lines is modified and reflected in an appropriate change in inductance. This change in inductance is the fundamental principle underpinning all eddy current methods[6] that rely on measurable changes in calibrated coil systems. A sensitive alternative is to monitor the changes in the sample inductor combination by resonating the system with a capacitor, which is the method set forth here.

The test configuration places the coils of the inductor tightly around the given sample to be tested for superconductor properties. The tight winding of the coil maximizes any relative change in the inductor brought about by a change in material property. This inductor-sample combination is then resonated with a capacitor, C, at a given frequency, f_o, and the resulting impedance, $Z(f_o)$, and phase, φ, are observed using an impedance meter (Figure 1). Such a resonant circuit is extremely sensitive to any change in lumped circuit parameters, and manifests such changes as phase-impedance or, equivalently, impedance-frequency deviations. It is this sensitivity that permits the RECA system to be used as a screening device for potential superconductors.

Operationally, the superconductor is cooled to a temperature well below what is thought to be its transition temperature. The sample-inductor is resonated using an appropriate capacitor. The sample then is permitted to slowly warm to the point where it becomes normal, while the frequency is held constant at the initial resonant frequency. During this warming period, the phase, φ, will exhibit small monotonic departures from the original value (which is normally equal to zero in a resonance) and may be easily monitored with a vector impedance meter. This change in phase with temperature (or time, if the warming is constant and linear) can be monitored easily and reflects a subtle temperature dependency in the material

[6] C.V. Dodd; et al; C.V. Dodd and W.E. Deeds (1982); C.V. Dodd and W.E. Deeds (May 1968).

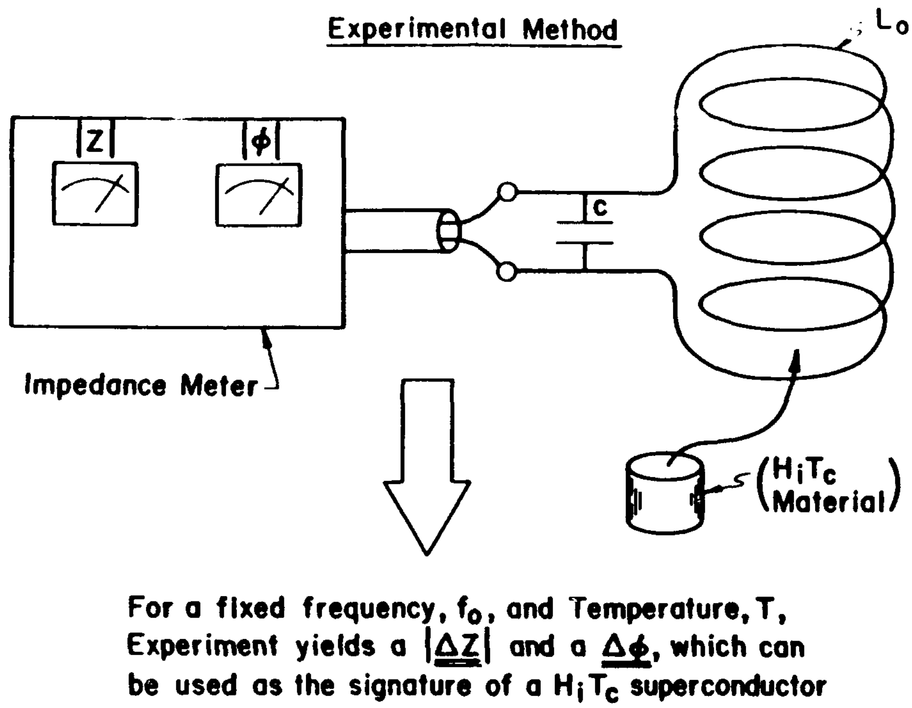

Figure 1. Test configuration.

properties. If the sample continues to be warmed through the superconducting transition temperature T_c, the phase will undergo a large and rapid increase brought about by the loss of superconducting properties upon entering the normal state. This pronounced change in phase over a narrow temperature (or time) range constitutes a well defined screening signature (Figure 2) and designates the sample for more detailed tests.

A particularly useful test is available directly from the screening procedure, provided the warming is done so the sample remains isothermal at any instant in time. In such circumstances, the phase can be reliably monitored as a function of the sample's temperature. A featureless and abrupt change (a fraction of a degree Kelvin, for HiTc materials) in the phase with respect to temperature indicates that the sample is monophasic and has a well developed crystal structure (Figure 2). However, if a broad phase change with respect to temperature occurs (some 5 to 10 degrees Kelvin for HiTc materials) and the transition region is characterized by sloping plateaus, the signature is of a polycrystalline sample containing more than one material phase. This information can be crucial in controlling process parameters used in fabricating new test samples.

RECA Sensitivity

The limiting factor in using RECA as a screening agent is the ability to discern the change of phase signature that arises as the sample undergoes the superconducting-to-normal material transition. This transition signature is normally superimposed on a slow drift in the circuit phase brought about by any small changes in material properties in either the superconducting or normal phase, usually the result of a temperature change during the warming process. The ability to resolve this signature from any random

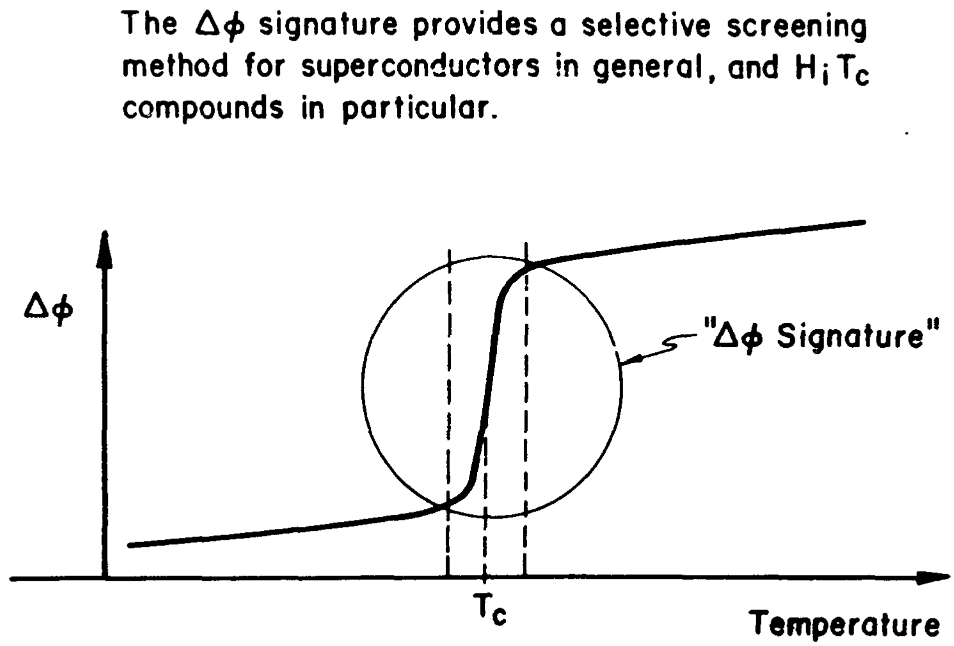

Figure 2. Phase change through transition temperature.

variations, including temporal changes, is improved by having the sample fill the inductor's interior volume. Further, any permanent record, such as a plot (Figure 2), can help resolve the signature from the drift or fluctuations, with the ultimate limitation being the signal-to-noise ratio in the phase detection circuit or the impedance circuit. This distinction is worthy of some clarification and highlights some of the intrinsic versatility of RECA.

Both the phase, φ, and the impedance, Z, are interdependent circuit parameters, both in and out of circuit resonance. Their magnitudes and sensitivities to changes in any lumped circuit parameter are a function of the frequency at which the circuit becomes resonant. For a given inductor-sample, this resonant frequency depends on the particular choice of capacitance, C (Figure 1). Thus, by varying C, screening can be performed at a number of frequencies. This extra degree of freedom affords access to frequency dependent features of the superconductor, and uses the φ, Z interdependence.

Because RECA is inductive in nature, one might expect greater sensitivity at higher frequencies ($\Delta Z \sim (\Delta L)\omega$), a fact which is born out in experiment. Further, if the L-C system is made to resonate ($\varphi \equiv 0°$) at frequencies slightly above (f_+) and below (f_-) the transition temperature, large absolute changes can be seen in both the impedance ΔZ and the resonant frequency $\Delta f \equiv (f_+ - f_-)$, associated with passing between the superconducting and normal state at these elevated frequencies. As the resonant frequencies become lower and lower, the Δf and ΔZ become progressively smaller, with a corresponding loss in sensitivity. However, the fractional change in frequency ($\Delta f/f_o$) is actually larger than at the higher frequencies.

3 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The RECA method was developed as an alternate screening analysis to supplement the more traditional resistive method of assessing HiTcS compounds' practicality as candidates for EMP shielding and other electromagnetic applications. The RECA methodology has the following attributes:

1. The method provides a contactless, timely, and efficient alternative to traditional resistive methods for ascertaining existence of superconductivity; the later being labor intensive and time consuming. Further, since the method is inductive (and therefore contactless) it can provide a more accurate measure of a sample's bulk critical current density by avoiding local resistive heating in the electrical contacts.

2. The method is inexpensive, requiring only an inductor, several capacitors, and an impedance meter (common pieces of laboratory equipment).

3. The method has high intrinsic sensitivity, which can be maximized by configuring the inductor tightly about a given sample.

4. The method provides a definitive signature unique to superconductors undergoing a magnetic phase transition.

5. The method does *not require* the conducting regions of a given sample to be in contiguous contact, unlike traditional resistive methods used in thin film work. This is particularly important when preparing thin films by ballistic deposition techniques since they can have local variations in chemical stoichiometry of the order of several micrometers or greater. It is important to note however, that conducting material dispersed in isolated islands will provide a noticeably weaker signature than the same material in a contiguous geometry.

6. The method can provide valuable sample quality information for properly thermostated samples. Examining the breadth and structure of the phase-temperature signature can provide evidence of a well developed crystal structure and the presence of more than one material phase in HiTcS materials.

Recommendations

RECA methodology is recommended in future research involving electromagnetic properties of superconductors. RECA is particularly appropriate for research involving material preparation techniques for HiTcS and inductive shielding simulations below 100 MHz. The method has further utility for nondestructive small sample quality assurance and noninvasive conductivity determinations.

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